Research on Balanced Winding Used in 3Y/3Y-pole-changing Motor

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Abstract

To address the imbalance problem among branches per phase in 3Y/3Y-pole-changing motor, this paper proposes the concept of balanced winding, explains the method of constructing it in detail and presents the general derivation process of its magnetomotive force. Useful conclusions were obtained after analyzing the harmonic magnetomotive force of balanced winding with specified pitch through an example.

Keywords

Winding; Winding Factor; Magnetomotive Force; Harmonic

Introduction

A motor's pole pair number can be altered by changing its winding connection. As the main supporting equipment to drive a fan or pump, a pole-changing motor with various speed and output power can adjust its mechanical property to meet load requirement. Compared with variable frequency control, pole changing control has some advantages such as lower device investment, less maintenance cost and lighter harmonic pollution, even though this control method regulates speed within a narrower range. Reasonably-designed and precisely-manufactured pole-changing motors can offer decent performance in the occasion of non-strict request for speed regulation.

There are two approaches to change the pole number of a winding: Inverse pole-changing and phase conversion pole-changing. The former approach simply converts current direction in a few coils without changing the assignment of slots, while the latter redistributes some slots to other phases. Although in some cases the latter approach may increase the number of lead wires, it can achieve higher distribution factors. Phase conversion pole-changing motors usually adopt the 3Y/3Y conjunction mode with only six lead wires. In this mode, extra circulation losses of stator windings might be produced if branches in each phase were unbalanced. Splitting coil is invented to

reduce losses. However, the calculation to determine coil split ratio is relatively complicated and the calculation result is quite different from the ideal value.

To design pole-changing motor winding, a twin-pole-pairs slot-number phase diagram is put forward, on the basis of which this paper comes up with the idea of balanced winding as well as its construction method and constraints. Moreover, the general derivation process of its magnetomotive force is given. Using balanced winding with small harmonic content under 3Y/3Y connection mode with six lead wires can not only make full use of the winding but also address the imbalance among branches belonging to the same phase.

Construction Method of Balanced Winding

Judgement on the Feasibility of Balancing Branches

Judging on the feasibility of making branches balanced refers to determining the possibility of constructing balanced winding for the given slot number and two different pole pair numbers.

The given slot number and two different pole pair numbers are represented with "Z" and "p_1, p_2". The expressions of the slot number per pole per phase are as follows:

$$\begin{cases} q_1 = \dfrac{Z}{6p_1} = \dfrac{N_1}{D_1} \\[2mm] q_2 = \dfrac{Z}{6p_2} = \dfrac{N_2}{D_2} \end{cases} \tag{1}$$

In the expressions above, "D_1, N_1" and "D_2, N_2" are two pairs of irreducible positive integers. Meanwhile, "D_1, D_2" must be less than "N_1, N_2" respectively.

If the following five constraints are all met, winding can be balanced. (N^* represents any positive integer.)

i. $N_1N_2 = 6N^*$.

ii. $Z = 6N_1N_2 = 6N^*$.

iii. $N_1 = 4$ or $N_2 = 2$.

iv.   The values of D_1 and D_2 are even numbers or 1.

v. $p_1 \neq 2N^*p_2$ and $p_2 \neq 2N^*p_1$.

The Twin-pole-pairs Slot-number Phase Diagram and the Valid Block

Essentially, twin-pole-pairs slot-number phase diagram is a table. It can be created by following the steps below:

1. Draw $6N_1$ columns in the horizontal direction corresponding to p_1 and $6N_2$ rows in vertical direction corresponding to p_2. Each row or each column corresponds to 2π electrical degrees.

2. Write positive slot number "1" in the top left cell. Then move D_1 columns in the horizontal direction and D_2 rows in the vertical direction, write positive slot number "2" in the appropriate cell, and so forth until all positive slot numbers are filled in.

3. Write negative slot number in the cell situated π electrical degrees from where the positive slot number is placed.

Firstly, divide the entire table into nine pieces evenly, and then split each piece into the left half and the right half. To ensure that slot numbers would not be chosen repeatedly, the right half should be removed. And what remains is a table with i rows and j columns. Define this table as the valid block. Fig. 1 shows how the valid block is constituted. As shown, when the pole number is p_1, the three valid blocks along the same horizontal direction, from left to right, correspond to Phases 1, 2 and 3 successively, and the three valid blocks along the same vertical direction, from top to bottom, correspond to Branches 1, 2 and 3 of that phase. Similarly, when the pole number is p_2, the three valid blocks along the same vertical direction, from top to bottom, correspond to Phases 1, 2 and 3 successively, and the three valid blocks along the same horizontal direction, from left to right, correspond to Branches 1, 2 and 3 of the phase.

The Procedure to Balance the Winding

For Column l of a valid block, count the cells that contain the slot number, then set the total to be $a_l(l=1,2,...,j)$, and for Row k, to be $a_k(k=1,2,...,i)$. For Branch $n(n=1,2,3)$ of Phase $m(m=1,2,3)$ corresponding to p_1, express its slot distribution by using $(a_1,a_2,a_3,...,a_j)_{mn}$, which is a j–dimensional
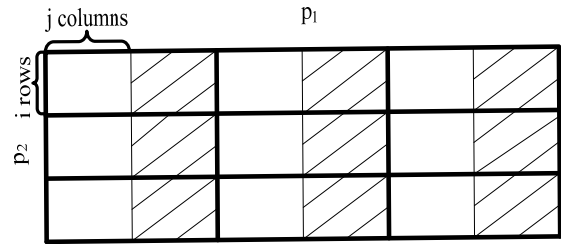

FIG. 1 DIAGRAM DESCRIBING THE CONSTITUDE COURSE OF THE VALID BLOCK

vector, and for Branch $n(n=1,2,3)$ of Phase $m(m=1,2,3)$ corresponding to p_2, express its slot distribution by using $(a_1,a_2,a_3,...,a_i)_{mn}$, which is a i–dimensional vector. Of the six vectors with the same phase value, three of them must be equal. Double the coil turns in the slot that corresponds to $a_x = 1(x = k$ or $x = 1)$ to equalize the other three vectors.

By following the procedures outlined above, three branches of any phase will be balanced and the three phases will be symmetric, no matter what the pole pair number is.

The Magnetomotive Force of Balanced Winding

To determine the magnetomotive force of each order harmonic per phase, first find out that per coil and then synthesize the same order harmonic magnetomotive force vectors of all coils belonging to the same phase.

If alternating current ($i_c = \sqrt{2}I_c \sin \omega t$) is applied to a coil with N_c turns, the magnetomotive force of this coil can be expressed as:

$$F_c(x) = F_{c1}\cos x + F_{c2}\cos 2x + F_{c3}\cos 3x + \cdots + F_{cv'}\cos v'x + \cdots$$
$$= \sum_{v'=1}^{\infty} F_{cv'}\cos v'x \qquad (2)$$

The abscissa of air gap circumference (mechanical radian) is represented with x.

$F_{cv'}$, the harmonic magnetomotive force amplitude when pole pair number equals to $v'(v' = 1, 2, 3, ...)$, can be obtained through Fourier integral. The expression is as follows:

$$
\begin{aligned}
F_{cv'} &= \frac{2}{\pi} \int_0^{\frac{y_c}{2}} (1 - \frac{y_c}{2\pi}) i_c N_c \cos v' x dx \\
&\quad - \frac{2}{\pi} \int_{\frac{y_c}{2}}^{\pi} \frac{y_c}{2\pi} i_c N_c \cos v' x dx \\
&= i_c N_c [\frac{2}{\pi}(1 - \frac{y_c}{2\pi}) \frac{1}{v'} \sin(v' \frac{y_c}{2}) \\
&\quad + \frac{2 y_c}{2\pi^2 v'} \sin(v' \frac{y_c}{2})] \\
&= \frac{2}{\pi v'} i_c N_c \sin(v' \frac{y_c}{2})
\end{aligned}
\tag{3}
$$

y_c — the pitch of coil

Set the pole pair number of the fundamental wave to be p and set v equal to v'/p. " v " is the harmonic order relative to the fundamental wave. The vth harmonic magnetomotive force amplitude per coil is expressed as follows:

$$
\begin{aligned}
F_{cv} &= \frac{2}{\pi} \frac{i_c N_c}{vp} \sin(v \frac{p y_c}{2}) \\
&= \frac{2}{\pi} \frac{i_c N_c}{vp} \sin(v \frac{y_c}{\tau} \frac{\pi}{2}) \\
&= \frac{2}{\pi} \frac{i_c N_c}{vp} k_{yv}
\end{aligned}
\tag{4}
$$

τ — polar distance of the fundamental wave

k_{yv} — short span coefficient of the vth harmonic

The vth harmonic magnetomotive force amplitude per phase is expressed as below:

$$
\begin{aligned}
F_{\Phi v} &= \frac{2}{\pi} \frac{a i_c N}{vp} k_{yv} k_{dv} k_{sv} \\
&= \frac{2}{\pi} \frac{i_\phi N}{vp} k_{yv} k_{dv} k_{sv}
\end{aligned}
\tag{5}
$$

a — the number of branches in parallel

N — the total of turns in series

k_{dv} — distribution coefficient of the vth harmonic

k_{sv} — chute coefficient of the vth harmonic

i_ϕ — phase current in motor stator

If three-phase symmetric current is applied to the balanced winding, the vth harmonic resultant magnetomotive force can be expressed as:

$$
\begin{aligned}
f_v(\theta_s, t) &= f_{1v}(\theta, t) + f_{2v}(\theta, t) + f_{3v}(\theta, t) \\
&= F_{1v} \cos \omega t \cos v\theta \\
&\quad + F_{2v} \cos(\omega t - 120°) \cos(v\theta - \theta_{12}) \\
&\quad + F_{3v} \cos(\omega t - 240°) \cos(v\theta - \theta_{13})
\end{aligned}
\tag{6}
$$

θ — space angle (electrical degree)

F_{1v}, F_{2v}, F_{3v} — the vth harmonic magnetomotive force amplitude of Phase 1, 2 and 3

θ_{12} — angle between the vth harmonic resultant magnetomotive force vector of Phase 1 and the vector of Phase 2

θ_{13} — angle between the vth harmonic resultant magnetomotive force vector of Phase 1 and the vector of Phase 3

The Winding Factor

It is known from the expression (5) that the harmonic amplitude of per phase is proportional to the winding factor of harmonic and inversely proportional to the harmonic order. Thus, the harmonic content could be analyzed through the winding factor " k_{wv} " and it is expressed by the three coefficients as below:

$$
k_{wv} = k_{yv} k_{dv} k_{sv}
\tag{7}
$$

The Short Span Coefficient

The short span coefficient of the vth harmonic can be evaluated by the following equation.

$$
k_{yv} = \sin(v \frac{y_c}{\tau} \frac{\pi}{2})
\tag{8}
$$

To make the coil turns identical in each slot, the pitch of balanced winding must meet the pitch constraints, that is, y_c isn't equal to the difference of any two slot numbers corresponded to the doubled turns coil.

The Distribution Coefficient

The distribution coefficient of the vth harmonic can be

calculated by the following equation.

$$k_{dv} = \frac{\left| \sum\limits_{k=1}^{M} \overrightarrow{F_{kv}} \right|}{\sum\limits_{k=1}^{M} \left| \overrightarrow{F_{kv}} \right|} \qquad (9)$$

$\overrightarrow{F_{kv}}$ — the vth harmonic magnetomotive force vector of the kth coil in one branch

M — the total of coils

The composite diagram of the vth harmonic magnetomotive force vector should be used to solve equation (9). The following points should be noted in constructing this diagram:

1. One branch of each phase is taken as the minimal unit.

2. Set the vector modulus of doubled turns coil to be 2, and the other coils to be 1.

3. For the coils in negative slot number, the minus sign before the harmonic magnetomotive force vector must be retained.

The Chute Coefficient

The balanced winding contains many tooth harmonics. To reduce these harmonics, sloping slot is adopted. The chute coefficients corresponded to the two pole pair numbers can be calculated by using two following formulas.

$$\begin{cases} k_{sv} = \dfrac{\sin v \dfrac{p}{Z} \pi}{v \dfrac{p}{Z} \pi} \\[4mm] k_{sv}{}' = \dfrac{\sin v \dfrac{p\tau_p}{Z\tau_p'} \pi}{v \dfrac{p\tau_p}{Z\tau_p'} \pi} \end{cases} \qquad (10)$$

τ_p — polar distance of the fundamental wave when pole pair number is $p(p = p_1$ or $p_2)$

$\tau_p{}'$ — polar distance of the fundamental wave when pole pair number is $p'(p' = p_2$ or $p_1)$

k_{sv} — chute coefficient when pole pair number is p

k_{sv} — chute coefficient when pole pair number is p'

Application Example

Take, for instance, the stator winding of 6/8-pole motor

in 3Y/3Y connection mode when $Z = 72$.

Through the analysis, it is known that slot number and two different pole pair numbers can meet the balancing constraints. Based on the method mentioned in Section 2, valid blocks with six rows and four columns are formed, as shown in Fig. 2.

Of the six vectors, the three 6–dimensional vectors are $(2,2,2,2)_{11}$, $(2,2,2,2)_{12}$ and $(2,2,2,2)_{13}$ respectively, and the others are $(2,1,1,2,1,1)_{11}$, $(1,1,2,1,1,2)_{12}$ and $(1,2,1,1,2,1)_{13}$, so the three branches corresponded to eight poles are imbalanced. To equalize these three vectors, double the coil turns in Slot 2, 3, 14, 15, 46, 47, 58, 59, 19, 30, 31 and 42. When m equals 2 or 3, its balancing method is the same as mentioned before.
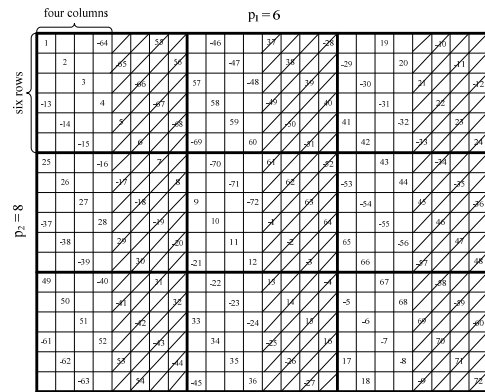

FIG. 2 THE TWIN-POLE-PAIRS SLOT-NUMBER PHASE DIAGRAM OF THE EXAMPLE

The connection mode of winding is shown in Fig. 3, and the number in square represents the doubled turns coil number.
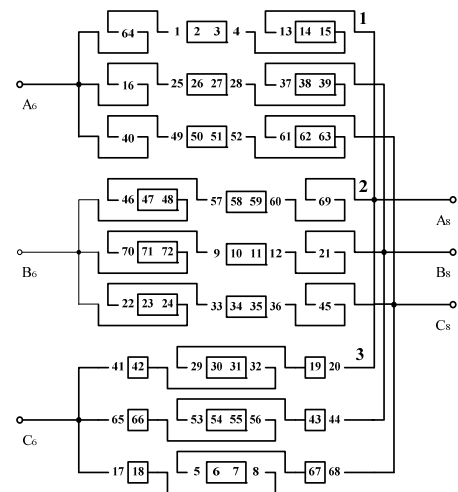

FIG. 3 THE FIGURE OF WINDING CONNECTION MODE

When the pole number is eight, the three branches of Phase A are not balanced. For these three branches, their composite diagrams of the fundamental wave magnetomotive force vector before balancing are shown in Figure 4(a), (b), (c). The composite diagrams after balancing are the same, as shown in Fig. 4(d), and the distribution factor is equal to 0.8312.
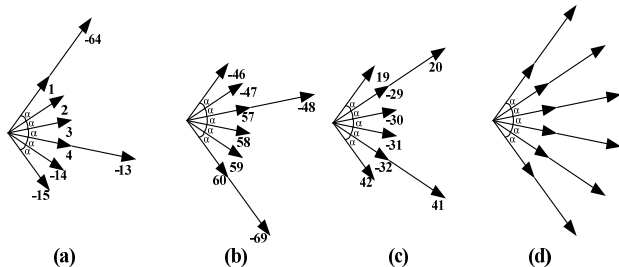

FIG. 4 THE COMPOSITE DIAGRAMS OF THE FUNDAMENTAL WAVE MAGNETOMOTIVE FORCE VECTOR BEFORE   AND AFTER BALANCING ($\alpha = 20°$)

When the pole number is six, the three branches of phase A are balanced. The same composite diagram of the fundamental wave magneto motive force vector before balancing is shown in Fig. 5(a), and the distribution factor is 0.9577. The composite diagram after balancing is shown in Fig. 5(b), and the distribution factor is 0.9689. Thus it can be seen that the distribution factor gets larger by using balanced winding.
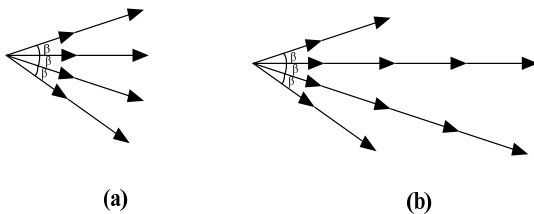

(a)   (b)

FIG. 5 THE COMPOSITE DIAGRAMS OF THE FUNDAMENTAL WAVE MAGNETOMOTIVE FORCE VECTOR BEFORE AND AFTER BALANCING ($\beta = 15°$)
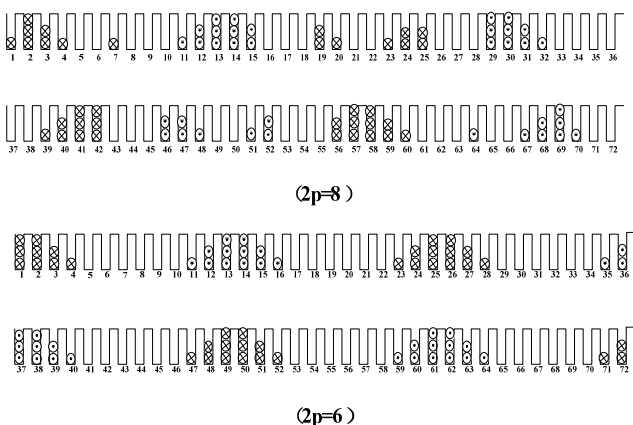

（2p=8）

（2p=6）

FIG. 5 THE WINDING DISTRIBUTIONS OF PHASE A

In this example, set the pitch y_c to be 10 to meet the pitch constrains. The winding distributions of Phase A are shown in Fig. 6.

By the method described in the previous section, the short span coefficient, distribution coefficient, chute coefficient and winding factor of each order harmonic are obtained as follows (see TABLE 1).

TABLE 1 WINDING FACTORS OF EACH ORDER HARMONIC

	k_{yv}		k_{dv}		k_{sv}		k_{wv}	
	2p=6	2p=8	2p=6	2p=8	2p=6	2p=8	2p=6	2p=8
1	0.966	0.985	0.969	0.831	0.997	0.995	0.933	0.815
5	0.259	0.643	0.401	0.188	0.930	0.878	0.097	0.106
7	0.259	0.342	0.098	0.154	0.866	0.769	0.022	0.041
11	0.966	0.342	0.041	0.154	0.689	0.489	0.028	0.026
13	0.966	0.643	0.041	0.188	0.583	0.338	0.023	0.040
17	0.259	0.985	0.098	0.831	0.357	0.059	0.009	0.048
19	0.259	0.985	0.041	0.831	0.245	0.052	0.003	0.043

Conclusions

In conclusion, the advantages of balanced winding are as follows:

- In 3Y/3Y connection mode, the number of lead wire is six, which makes motor system have high reliability.

- Under both two running states, the content of odd harmonic is small and the even harmonic don't exist at all.

- The distribution factor of the fundamental wave corresponded to a certain pole pair number gets larger.

- By using balanced winding, the circumfluence among branches per phase can be basically eliminated, which makes the three branches of each phase balanced.

Although the application scope of balanced winding is limited by constrains, this winding is so typical that it can be widely used in the step speed regulating occasion.

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